Fermi National Accelerator Laboratory

TM-1535

Explanation of Persistent High Frequency Density Structure in Coalesced Bunches

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July 26, 1988

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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Introduction

It has been observed that after the Main Ring RF manipulation of coalescing (where 5 to 13 primary bunches are transferred into a single RF bucket) the new secondary bunch displays evidence of high frequency density structure superimposed on the approximately Gaussian longitudinal bunch length distribution. This structure is persistent over a period of many seconds (hundreds of synchrotron oscillation periods).

With the help of multiparticle simulation programs, an explanation of this phenomenon is given in terms of single particle longitudinal phase space dynamics. No coherent effects need be taken into account.

The Coalescing Process

The process of coalescing[1] requires the execution of three Main Ring RF manipulations. First, there is the counterphasing operation, where the 800 kV amplitude of the 53 MHz (h=1113) RF voltage is adiabatically reduced to 2-3 kV. Figure 1 is an ESME[2] plot showing 0.05 eV-sec longitudinal 95% emittance bunches in 3 kV (0.36 eV-sec bucket area) RF buckets. Ideally, the RF voltage should be reduced until the bucket area equals the bunch emittance, therefore eliminating the empty spaces between the bunches. In reality, the bunch emittances are typically 0.09 to 0.15 eV-sec, and the performance of this process[3] has problems which are still not completely understood, limiting the minimum RF voltage to around 2 KV. Therefore, the figure is a qualitatively correct representation of the paraphasing process.

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1. Design Report Tevatron 1 Project, pg.6-4 (1983).
2. J. MacLachlan, "ESME: Longitudinal Phasespace Particle Tracking - Program Documentation", Fermilab TM-1274 (1984).
3. D. Wildman, P. Martin, K. Meisner, and H.W. Miller, "Bunch Coalescing in the Fermilab Main Ring", Proc. IEEE Part. Acc. Conf., Washington D.C., pg. 1028 (1987).

The second phase of the coalescing process is bunch rotation. When the primary bunches are sufficiently debunched by the paraphasing operation, a 2.5 MHz (h=53) RF voltage of approximately 26 kV is turned on. As shown in figure 2, the bunches rotate in longitudinal phase space until they all circulate in the accelerator at the same azimuth (as shown in figure 4). Looking at the time projection of this density distribution on various turns, one produces a "mountain range" of the bunch rotation process (see figure 3).

Finally, the 53 MHz RF voltage is snapped back on to recapture the bunches. A secondary coalesced bunch is born, with a larger longitudinal emittance and an initial density distribution modulation in the momentum plane. This residual bunch structure will now synchrotron revolve in that RF bucket.

Density Distribution Observations

The observation of persistent high frequency density structure[4] was made with the help of a mountain range plot. Figure 5 contains a mountain range photograph in which the time span of the image encompasses the entire coalescing process. The bottom trace shows the azimuthal density distribution of the bunch after the beam has been recaptured for one quarter of a synchrotron period. The structure which had been evident in the momentum plane has now rotated into the azimuthal plane.

This sort of phase space reappearance of primary bunch structure has been observed before[5] in the Fermilab booster synchrotron. What is surprising is that this structure persists for hundreds of synchrotron periods.

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4. P. Martin, Private Communication.

5. C. Ankenbrandt, E. Gray, J. Griffin, R.L. Sumner, and R.P. Johnson, "Reappearance of Linac Bunch Structure on Booster Bunches During Capture and Acceleration", IEEE Trans. Nucl. Sci., Vol. NS-24, No. 3, 1455 (1977).

Phase Space Dynamics

A proton with a very small synchrotron oscillation amplitude revolves in the RF bucket with a frequency equal to the synchrotron frequency (f_s). Because the RF voltage is sinusoidal, a proton with a synchrotron amplitude of θ radians oscillates with a lower frequency, given approximately by[6]

$$f(\theta) = f_s \left(1 - \frac{1}{16}\theta^2\right)$$

The exact relationship involves elliptical integrals. As shown by the phase space snapshots in figure 6, if the area of the primary bunches are small compared to the bunch separations, then over time the charge in each bunch smears out into bands of unique amplitude. After an infinite number of synchrotron oscillations, the charge distribution reaches the steady state situation depicted in figure 7.

Coalescing

Let us assume representative bunch and RF parameters, and simulate the phase space distribution of the coalesced secondary bunch as a function of time. The input variables are listed in the table below.

Variable	Value
Transition gamma γ_t	18.75
Radius	1000.0 meters
RF harmonic	1113
Beam energy	150.0 GeV
Recapture RF voltage	800.0 kV
Bunch Length (FWHM)	6.0 nsec
Fraction energy width (FWHM)	4.0×10^{-5}
Fraction energy bunch spacing	1.0×10^{-4}

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6. S. Ohnuma, "The Beam and the Bucket", TM-1381, Fermilab (1986).

Assuming that each primary bunch starts out Gaussian in both phase space directions, figures 8-10 show the secondary beam at the time of capture, and then at various numbers of a synchrotron periods later. Clearly, the primary bunch structure always persists in the form of a radial density distribution modulation. Azimuthal variations in the proton density disappear first at the largest amplitudes, smearing out at progressively smaller amplitudes as time goes on.

Conclusions

Observed persistent high frequency density structure in coalesced bunches has been explained in terms of single particle longitudinal phase space dynamics. Phase space scatter plots and azimuthal density histograms generated by multiparticle simulations were used to illustrate the arguments. No coherent effects were required in the model.

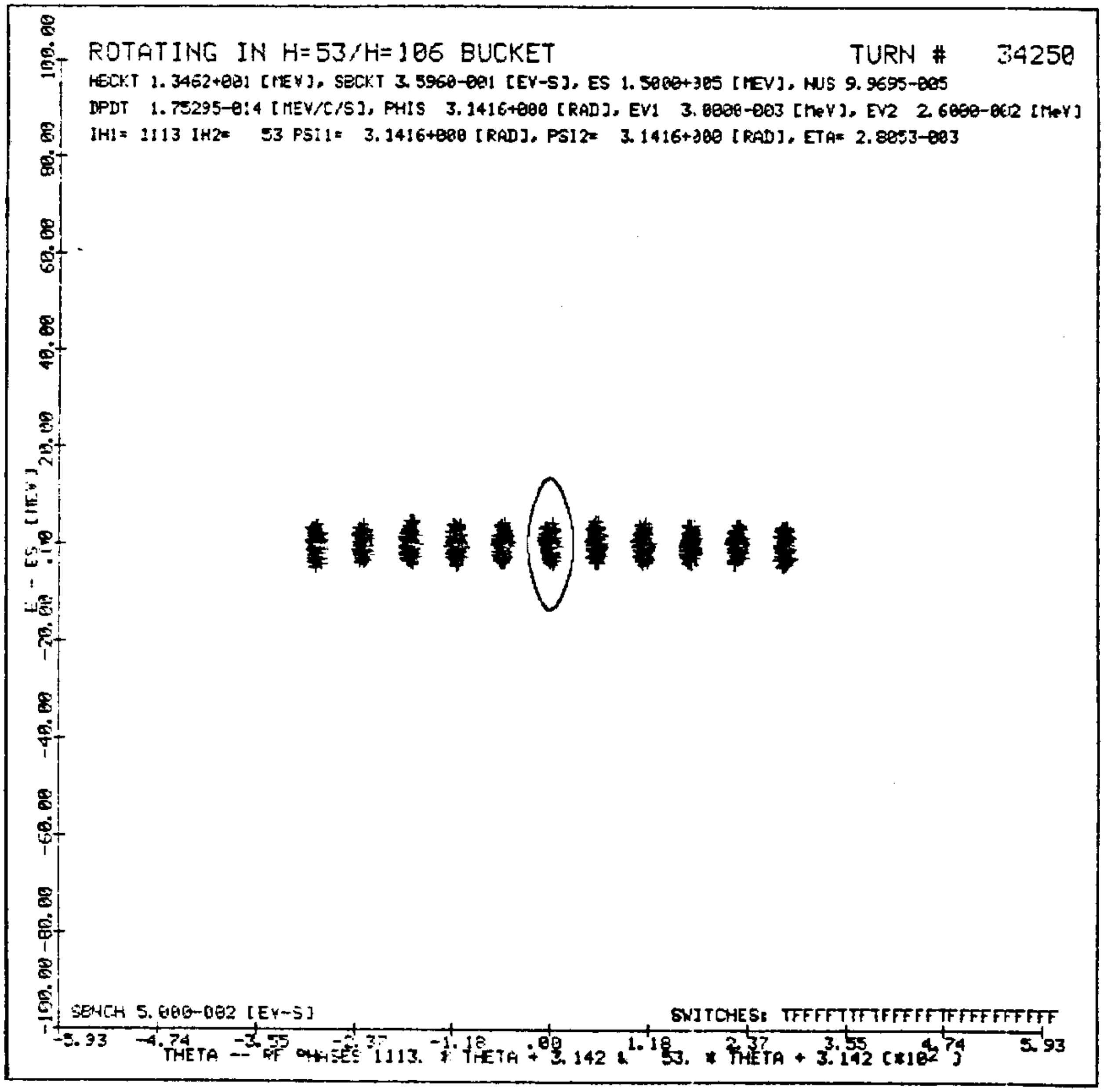

Figure 1: ESME program simulation result of the end of the paraphasing portion of the coalescing process. The vertical axis is energy deviation and the horizontal axis is phase. The RF bucket boundary is drawn around the center primary bunch.

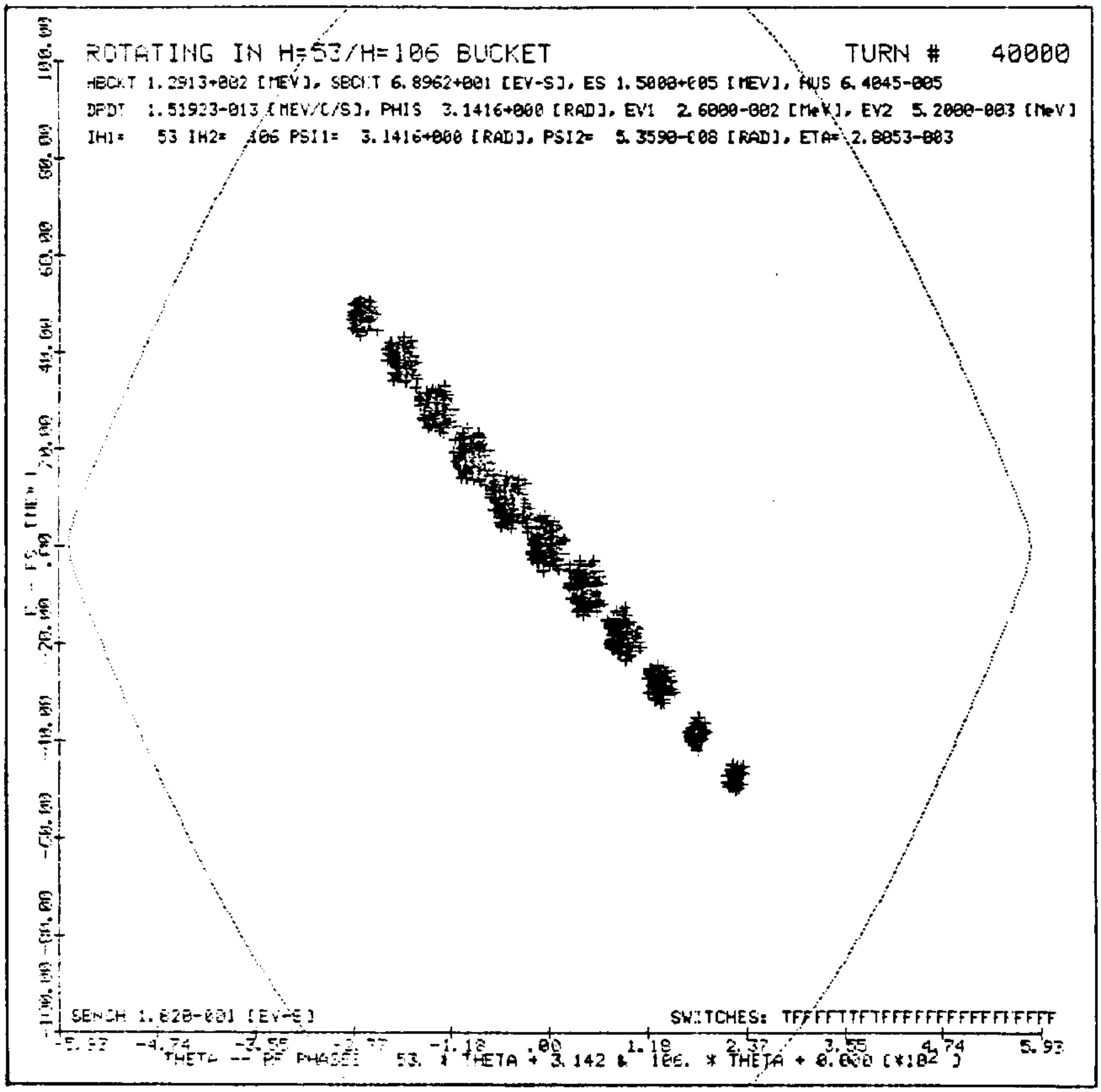

Figure 2: Simulation result at the middle of the bunch rotation segment of the coalescing process. The RF bucket is produced by the 2.5 MHz (h=53) system with a voltage of 26 kV.

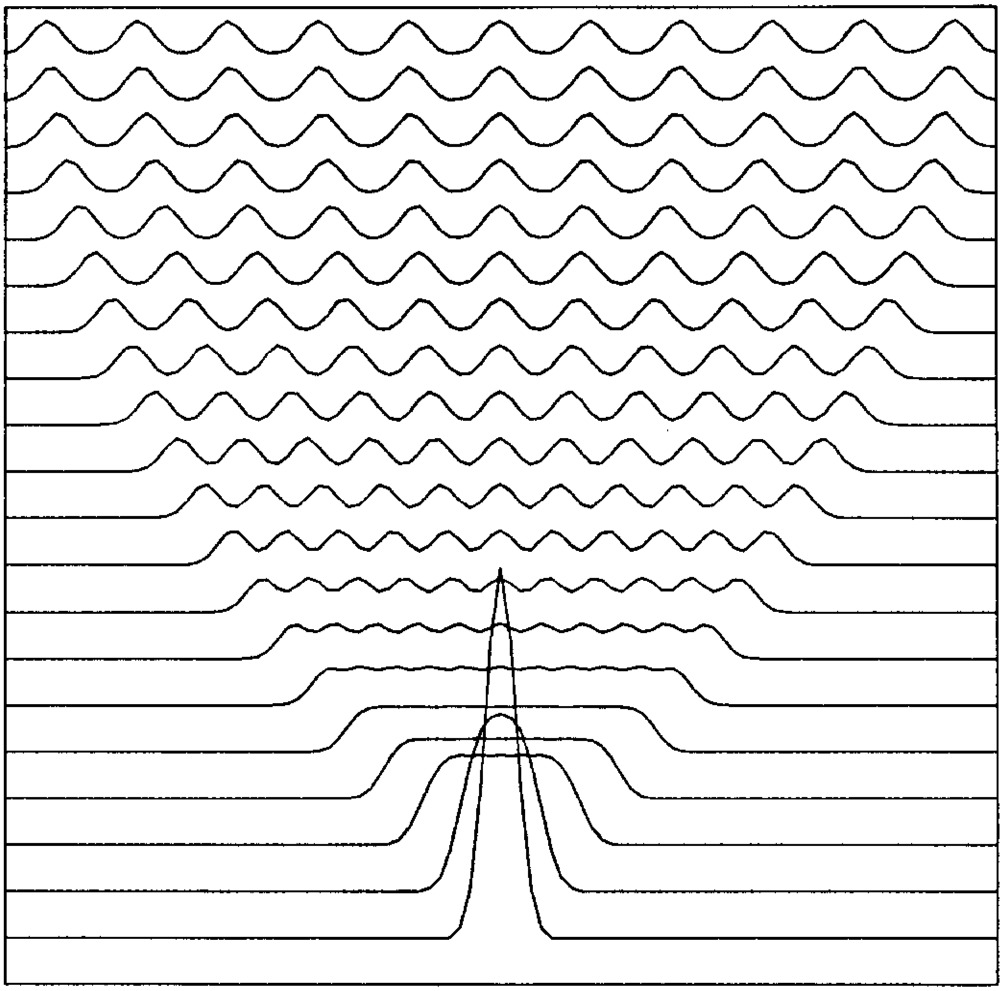

Figure 3: Calculated mountain range display of the primary bunch azimuthal density distribution during bunch rotation. Time is progressing from the top trace toward the bottom trace.

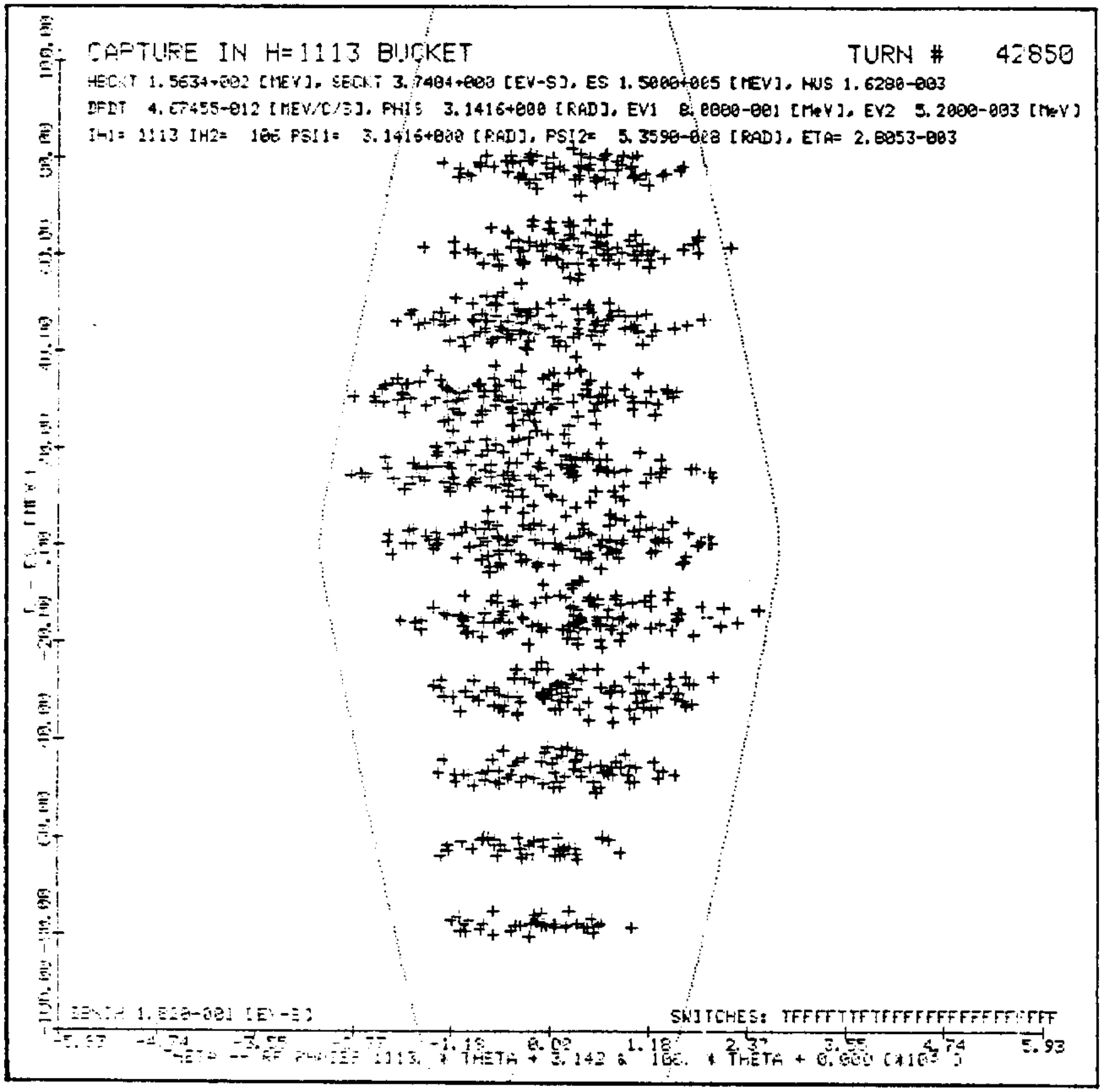

Figure 4: ESME simulation plot of the start of the bunch recapture portion of the coalescing process. The 53 MHz (h=1113) voltage of 800 kV is generating the RF bucket.

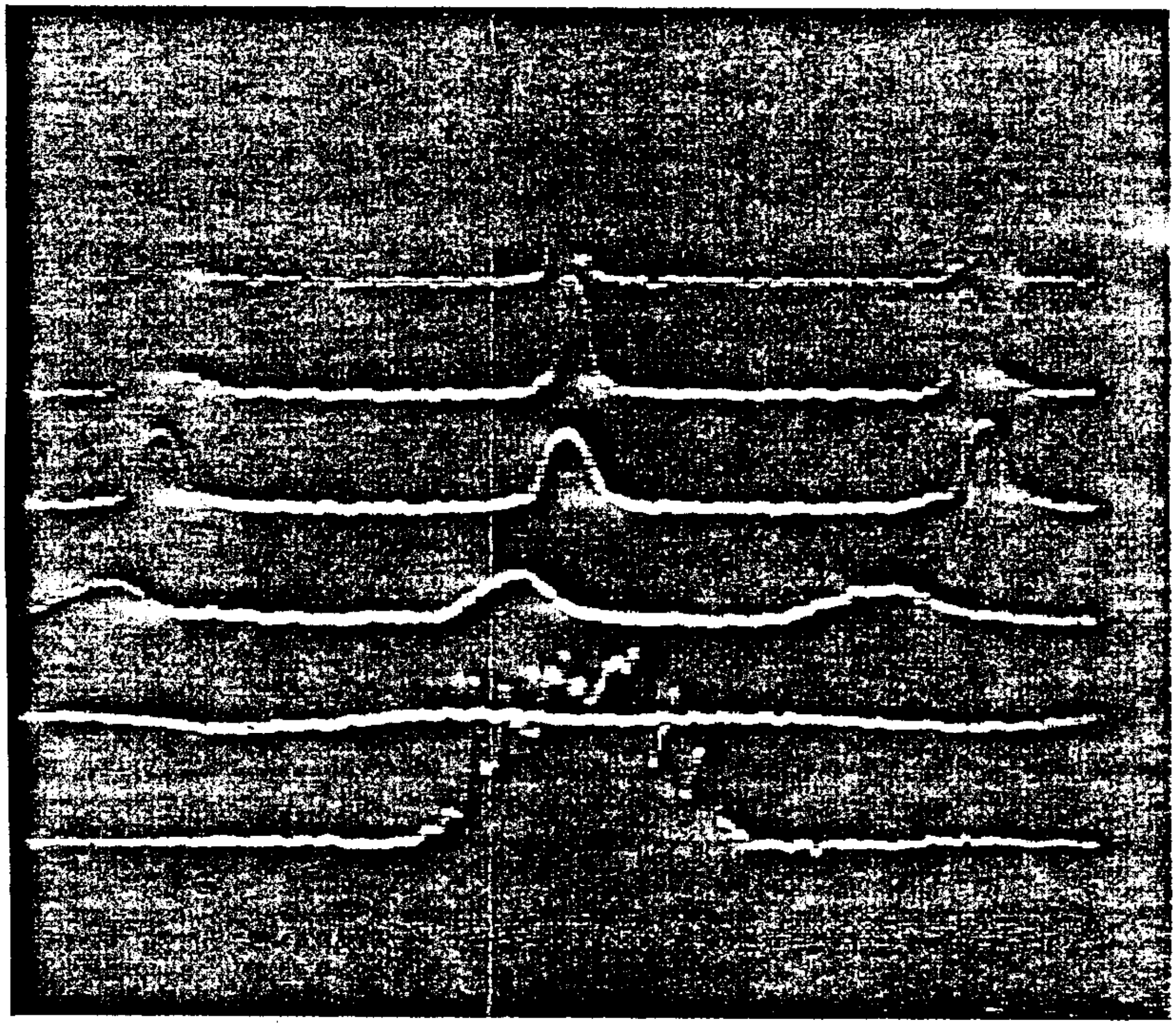

Figure 5: Actual mountain range plot of the proton azimuthal density distribution throughout coalescing. The bottom trace shows the secondary bunch one quarter of a synchrotron period after the bunch recapture stage. Note the approximately 1 GHz noise structure on the secondary bunch azimuthal density distribution. The primary bunches at the top of the photograph are separated by 18.9 nsec.

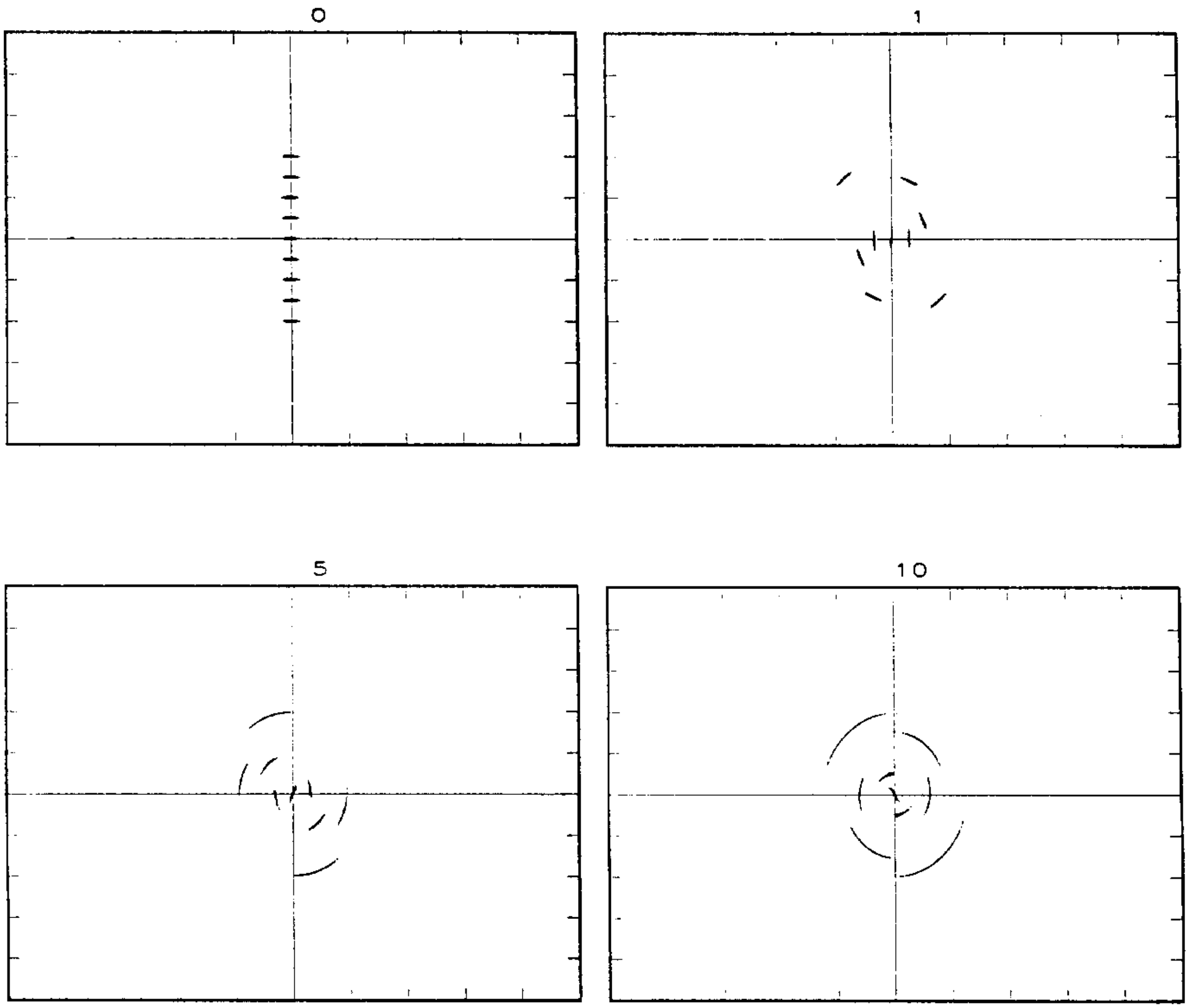

Figure 6: Simulation of the phase space distribution of small longitudinal emittance primary bunches as a function of time. The dependence of synchrotron frequency on amplitude, with its implications both between and within the bunches is clearly visible.

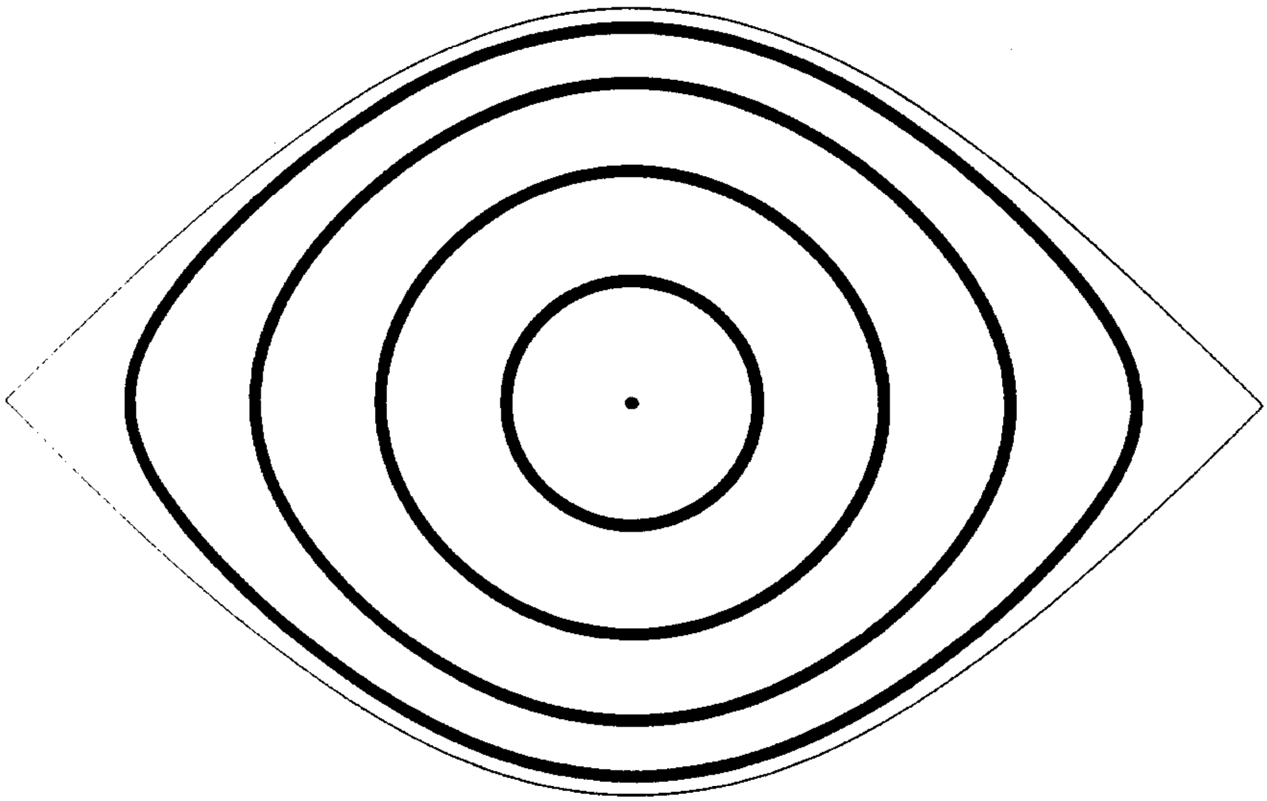

Figure 7: Calculation of the ultimate phase space distribution of small longitudinal emittance primary bunches.

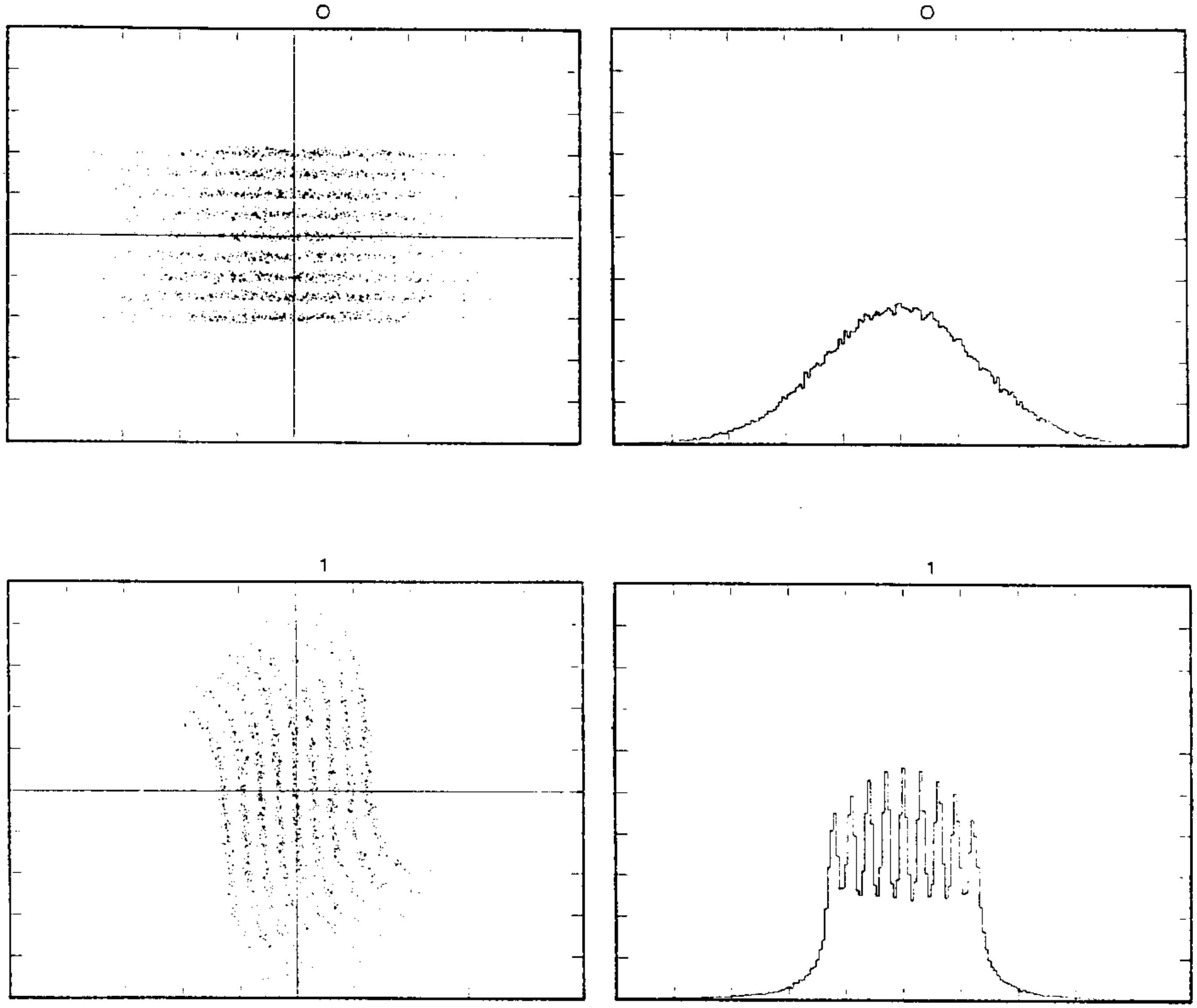

Figure 8: Phase space scatter plots and azimuthal histograms of the secondary bunch 0) at recapture time and 1) one quarter of a synchrotron period later.

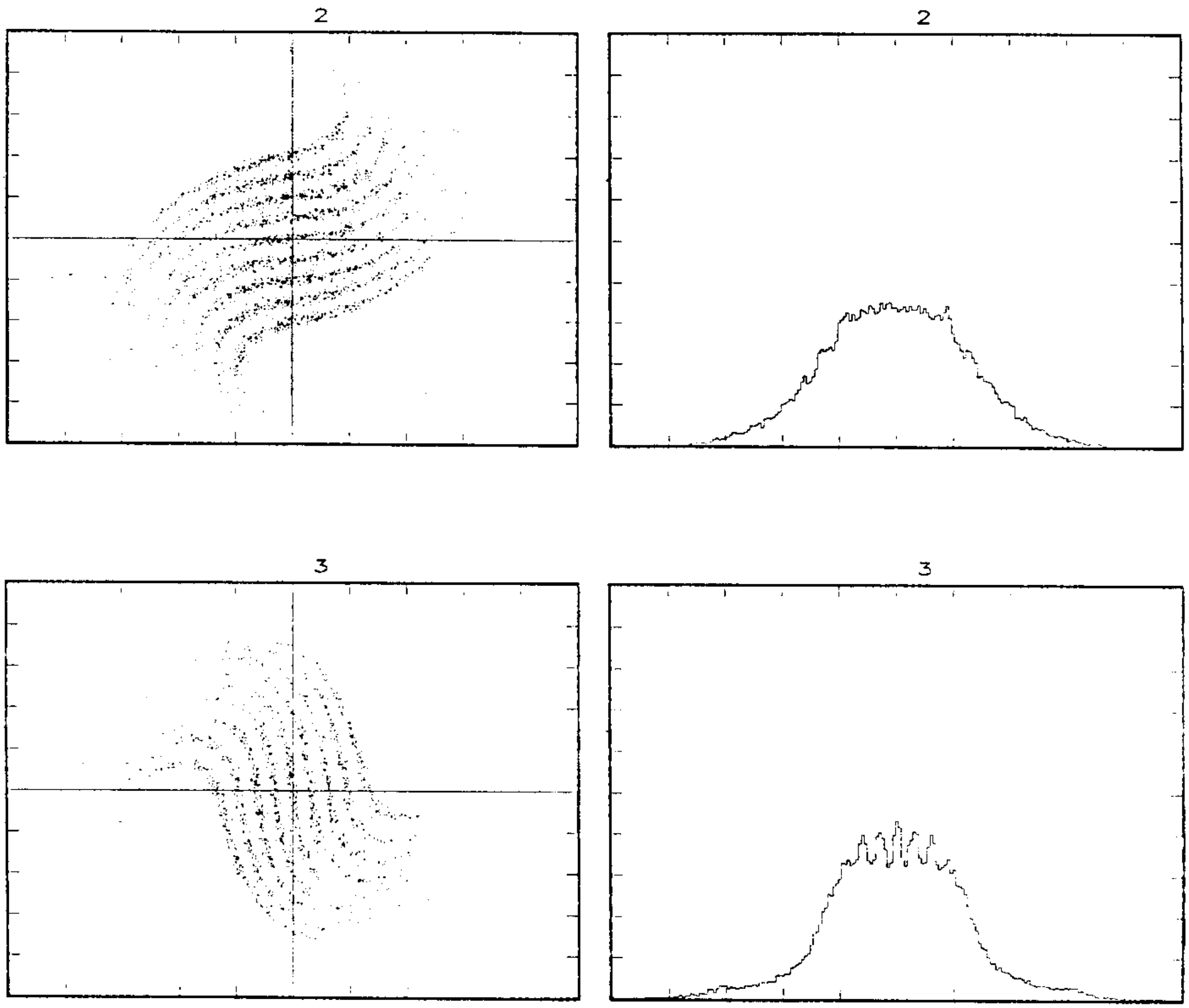

Figure 9: Phase space scatter plots and azimuthal histograms of the secondary bunch 2) one half of a synchrotron period after recapture time and 3) three quarters of a synchrotron period after recapture time.

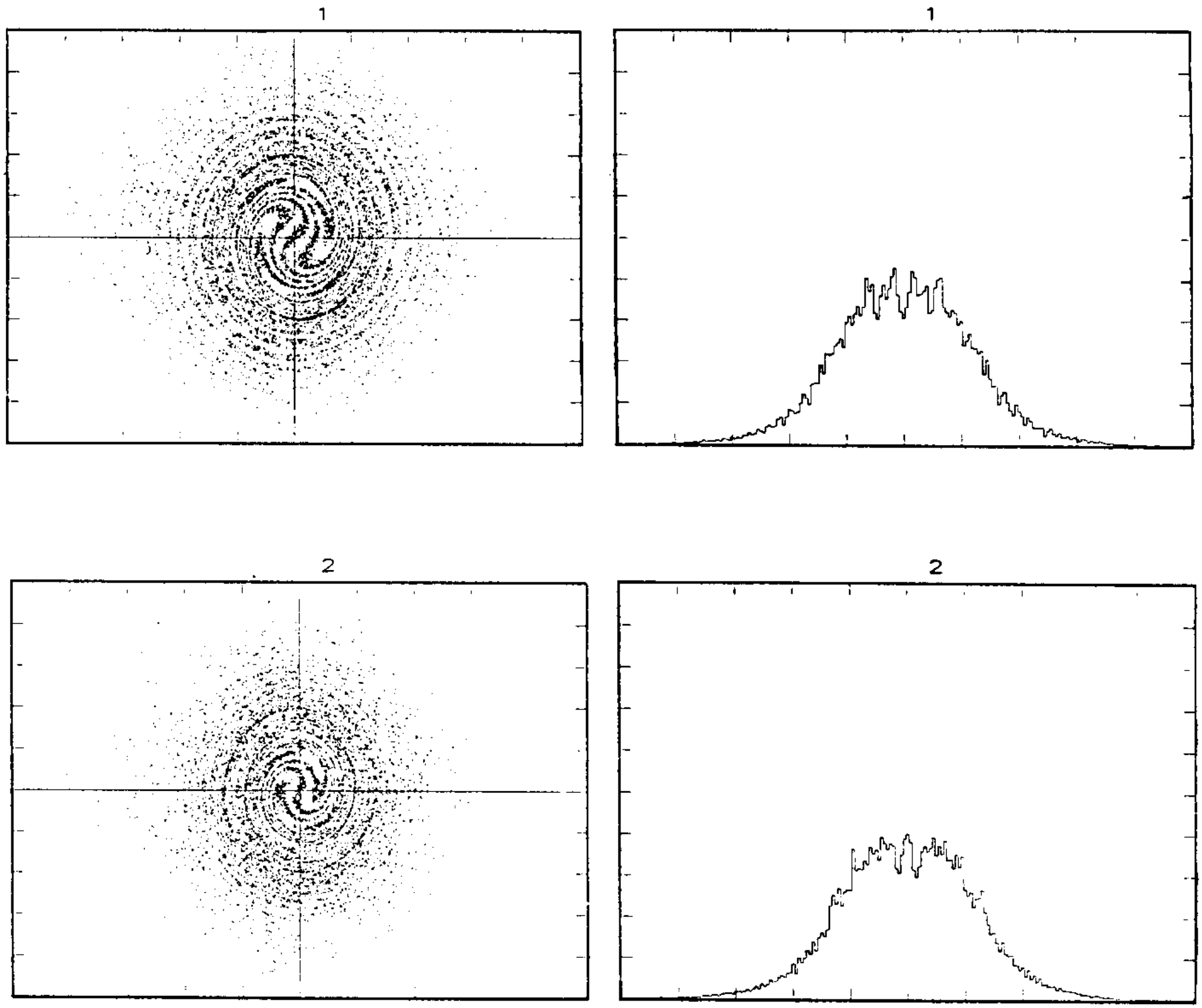

Figure 10: Phase space scatter plots and azimuthal histograms of the secondary bunch 1) 25 synchrotron periods after recapture time and 2) 50 synchrotron periods after recapture time.